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Industrial R&D Project Portfolio Selection Method Using A Multi-Objective Optimization Program: A Conceptual Quantitative Framework

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Abstract:

Purpose: Industrial R&D Project Portfolio Selection Method using a Multi-Objective Optimization Program – a Conceptual Quantitative Framework.

Design/methodology/approach: Research and development (R&D) activities are crucial if companies are to adapt to technology changes, but budget constraints and limited resources often force companies to select a subset of candidate projects through portfolio selection methods. However, existing models for R&D portfolio selection do not adequately consider interdependencies and types of projects, and this can lead to suboptimal selection and misalignment with corporate objectives.

Findings: A Multi-Objective Optimisation Program (MOOP) is suggested transcending from classic manpower, time, and financial planning into addition of strategic, skills and commercial objectives. A Pareto front is used as validation mechanism.

Research limitations/implications: Project selection processes are widened with select and critical quantitative positions. Potentials remain in areas of team capability, corporate capabilities, deeper skill understanding, and stakeholder engagement.

Practical implications: A quantitative validation is often overlooked in PPM project selection over more qualitative or idiosyncratic selection methods.

Originality/value: A quantitative validation is often overlooked in PPM project selection over more qualitative or idiosyncratic selection methods.

Keywords: R&D project portfolio selection, project portfolio management, portfolio value, strategic orientation, multi-objective optimization

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1. Introduction

Research and Development (R&D) portfolio decisions are complex as being dependent of unpredictability of innovation, competitor and markets issues, and general technological changes, which may give fuzzy or unreliable data and information conditions. Prioritizations within R&D project portfolio management (PPM) must constructively reflect resources, risks and opportunities (Wang & Hwang, 2007).

Competition is driving the demand for innovative solutions and technological development in the global marketplace requiring business excellence R&D prioritization (Killen & Hunt, 2010; Analia-Sánchez, Gastaud-Maçada & del Valle-Sagardoy, 2014). This is intensified by the complexity of the failure rates of new products and eventual lack of innovation performance, as 40% of new products are projected to fail at launch after the development and testing phase (Cooper, 2019). Companies that are engaged in R&D face challenges of project portfolio performance, selection, and decision (Wang & Hwang, 2007). The financial pressure to reduce time-to-market implies that projects do not often operate in isolation within an organization and are aligned with corporate strategic priorities (Too & Weaver, 2014). Simultaneously, this pressure increases the number of projects within an organization, and subsequently the complexity of managing the projects' interdependencies and business value priorities (Too & Weaver, 2014; Killen, 2017). This is where PPM comes into play (Killen & Hunt, 2010; Meskendahl, 2010; Killen, 2017).

The purpose of integrating a PPM framework is to make a decision-making method that allocates, to a restricted and controlled set of projects, resources, calculated risk, reward, and alignment of corporate strategy (Wang & Hwang, 2007; Analia-Sánchez et al., 2014; Killen, 2017). A project portfolio is a set of projects that share and compete for scarce resources (Meskendahl, 2010). The competition for and coordination of these resources is carried out by budget sponsors, which are entities providing funding for the particular projects. Transparent and excellent management of the portfolio is expected to increase the competitional position of the organization (Meskendahl, 2010). Selecting the 'optimal mix of projects' is the pre-eminent task within existing organizational capacities (Meskendahl, 2010; Killen & Hunt, 2010). Characteristically, companies have multiple strategic initiatives in place that can foster or impede success (Kunisch, Keil, Boppel & Lechner, 2019). Therefore, the focus for PPM should be on the overall portfolio and performance instead of individual strategic initiatives (Killen & Hunt, 2010; Kunisch et al., 2019). However, Too and Weaver (2014) argue, one of the primary causes of performance issues in projects is the existence of misaligned or underdeveloped governance mechanisms. To address these issues, it is necessary to improve the governance structures in place to enable a more flexible and robust response to the challenges faced during a project (Too & Weaver, 2014).

This paper is inspired by and builds on the strategic orientation concept of Meskendahl (2010) by incorporating business strategy and performance (Killen & Hunt, 2010; Meskendahl, 2010; Analia-Sánchez et al., 2014). By merging the framework of Meskendahl (2010) and framework elements from Litvinchev, López, Escalante and Mata (2011), Rabbani, Najjarbashi and Joudi (2013), Baqeri, Mohammadi and Gilani (2019) and Dixit and Tiwari (2020), this paper creates a multi-objective optimization program (MOOP) as a project portfolio selection method that is an accurate method for analysing R&D projects in a systematic manner to optimize corporate objectives. The objectives consider the values and risks of proposed projects in a multi-project, multi-opportunity context helping managements' decision making. By developing a selection method to balance the desirable business and performance outcomes, corporate profit and strategic alignment for the R&D portfolio are enabled for a risk-averse decision maker in an uncertain environment (Abbassi, Ashrafi & Tashnizi, 2014; Killen, 2017). The portfolio selection method is a mathematical model developed from a risk and business value perspective. The mathematical programming model optimizes a multi-objective function subject to constraints related to strategy, resources, risk, profit, and dependencies. It depends on the flexibility within the resources, and from the set of optimal solutions, the sensitivity can be analysed by looking at the different scenarios. The MOOP is intended to fit within the elements from multiple research frameworks to propose a new framework for the systematic selection and adjustment of an R&D project portfolio that has the highest probability of advancing the organization's objectives, which are aligned with its strategies, while minimizing portfolio risk, within the organization's constraints on resources such as personnel and funding.

Figure 1 emphasizes the way this paper merges different frameworks (Meskendahl, 2010; Litvinchev et al., 2011; Rabbani et al., 2013; Baqeri et al., 2019; Dixit & Tiwari, 2020). However, the elements compiled within Figure 1 are not addressed in qualitative business extended research. The implementation of the concept and the contribution of each element within Figure 1 take place in the context of solving the MOOP, and the framework applies the non-dominated sorting genetic algorithm (NSGA-II) (Verma, Pant & Snasel, 2021). Therefore, this merged framework is formulated and strategized as a comprehensive conceptual model, where each element is considered as an input and an output, which is part of a larger governance process (Abbassi et al., 2014). The merged framework is described and presented in detail to highlight the relationship between the elements.

Figure 1 presents an overview of the general framework employed in this paper. It suggests that the impact of strategic orientation on business success is influenced by the interplay between portfolio structuring, the MOOP and project portfolio construction. Additionally, it proposes that strategic orientation moderates and aggregates, as a mechanism in the relationship between project portfolio structuring and the MOOP, which respectively moderates the project portfolio construction.

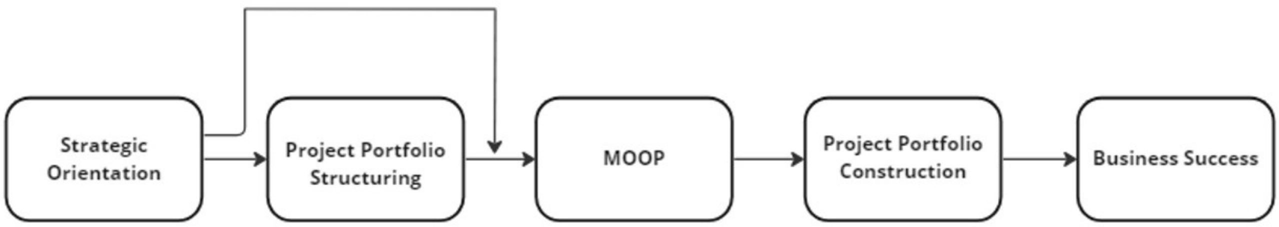

Figure 1. Overview of general framework

The framework address issues arising in relation to a case company within the northern European renewable energy industry that does not have a PPM. This is done to test its applicability in a real-world scenario. The organization drives its project management (PM) by emphasizing 'best practices' and using subjectivity, with limited information to support organizational strategies. Furthermore, there is no measurement of project portfolio performance or risk management. This framework is applied to the R&D division in the case company, resulting in a method to quantitatively evaluate the framework to maximize portfolio values as opposed to portfolio risks and project dependencies.

This leads to the research question for this paper: How can an R&D project portfolio selection model and solution method be formalized as an initial procedure for a project organization?

One of the essential aspects is that the evaluation method utilized in the assessment of this research should be appropriate for the variety of projects in the R&D division being examined.

In the context of R&D, the selection of projects for inclusion in a portfolio is inherently complex because of the uncertain nature of these endeavours. An important challenge in using portfolio methods for this purpose is the identification and use of relevant variables and indicators to accurately assess the potential value and feasibility of proposed projects. There is a need to carefully consider which variables to include in the evaluation process so that informed decisions are made about the suitability of individual projects for inclusion in the portfolio. However, to effectively create a method for decision-making regarding project portfolio selection requires the creation of a model that combines various methodologies. This is done to mitigate their respective limitations and determine the optimal solution algorithm in terms of both solution quality and computational efficiency. The model should be designed to facilitate the selection of a balanced portfolio of R&D projects that maximizes value and feasibility. Tavana, Keramatpour, Santos-Arteaga and Ghorbaniane (2015) confirm that the complexity of portfolios is dependent on contradictory goals, coherent project dependencies, data uncertainty in relation to project performances and criteria, and organizational constraints or boundaries.

2. Theoretical Background and Literature Review

PPM and its implied objectives as set out by Cooper, Edgett and Kleinschmidt (2002) are established in the project management literature. The main goals are the maximization of the financial value of the portfolio (Meskendahl, 2010; Cooper & Sommer, 2020), while fitting in with the corporate strategy, and balancing the projects within defined limitations for the portfolio such as corporate capacity (Meskendahl, 2010). The method includes project valuation, ranking, selection, and criteria for risk analysis (Pajares & López, 2014; Hyväri, 2014; Killen, 2017). This is attained in six areas: maintaining portfolio alignment to strategic objectives, allocating financial resources, allocating human resources, allocating material or equipment resources, measuring portfolio component performance, and controlling risk (Hyväri, 2014).

Gradually, research on PPM has recognized that different practices are considered necessary in different contexts, following a contingency theory argument (Martinsuo, 2013). Therefore, it must be emphasized that capabilities for the recommended PPM initiatives and structure are developed over time with a learning effect on PPM performance (Martinsuo, 2013). Therefore, by merging elements from the conceptual frameworks proposed by Meskendahl (2010), Litvinchev et al. (2011), Rabbani et al. (2013), Baqeri et al. (2019) and Dixit and Tiwari (2020), the extensive research done in this context leads to a project selection and business evaluation method that can be applied to a range of multi-stage portfolio problems and handles uncertain and flexible parameters (Abbassi et al., 2014; Analia-Sánchez et al., 2014; Killen, 2017).

Wang and Hwang (2007) argue that PPM can be divided into three categories: strategic management tools, benefit measurement methods, and mathematical programming approaches. Strategic management tools, such as a portfolio map, a bubble diagram and so on, are used to emphasize the link between innovation projects within the portfolio to balance the strategy of the portfolio. The benefit measurement methods arguably emphasize the preferability figure for each project in the portfolio, and follow a variety of approaches, such as the merit-cost value index and the net present value, which is taken into consideration in the PPM to estimate the benefit of each project. The identification and indication of the projects with the highest score may or may not be done sequentially. The mathematical programming models optimize objective functions subjectively against a defined set of constraints, such as final resources, logistics, and human capabilities. The project selection models can be defined as linear, nonlinear and integer problems that capture an optimal project portfolio by selecting the right set of projects and investigating the sensitivity of the estimated project value.

To capture the PPM performance, the overall success criteria are divided into three dimensions: process effectiveness, portfolio success, and portfolio-related corporate success (Jonas, 2010). Jonas (2010) defines the success measurement as set out below:

Process effectiveness: There are three complementary constructs here: information quality, allocation quality, and cooperation quality. Jonas (2010) argues that these are closely related and essential for success.

Portfolio success: This is the average project success over all projects regarding the constraints of time, budget and scope, and the exploitation of synergies between projects that might additionally increase the overall portfolio value, the strategic fit to the corporate strategy, and the balance of risk.

Portfolio-related corporate success: The literature separates corporate success into market success and commercial performance. Market success describes sales objectives or sales volumes. Commercial success measures are derived from return on investment, profitability, or time to break-even.

Based on the three dimensions proposed by Jonas (2010), it can be noted that the selection of a project for a portfolio is a practice that requires the assessment of more than one parameter.

The selection of projects to be included in the portfolio should comply with the objectives identified by the organization (Ghasemzadeh & Archer, 2000; Killen & Hunt, 2010; Analia-Sánchez et al., 2014; Cooper, 2022). Exploring the scenarios for project portfolio compositions that achieve the optimal objective value can, for complex project portfolios, involve the consideration of many unique conditions and constraints. It is essential to compose the project portfolio without exceeding the accessible resources or violating other constraints involved (Ghasemzadeh & Archer, 2000). In relation to the project portfolio composition, an increase in the number of candidate projects equates to an increase in the complexity of the decision process (Tavana et al., 2015). The quality of the selection decision process has a critical impact on the feasibility of the project execution and the benefits gained from the use of company resources (Rabbani et al., 2013; Analia-Sánchez et al., 2014; Killen, 2017; Cooper, 2022).

The task of selecting project portfolios is a significant and recurring activity (Archer & Ghasemzadeh, 1999; Cooper, 2022). The propositions for project selection for the portfolio in the case company are those defined by Archer and Ghasemzadeh (1999) as projects that must compete for scarce company resources available from sponsors to meet the minimum requirements as a periodic activity. Therefore, the projects that are competing for scarce resources are defined as project proposals and projects in the idea phase (Archer & Ghasemzadeh, 1999) before they get a project approval and mandate in the R&D division.

Exploring the optimal project portfolio composition may require an assessment of more than one objective (Litvinchev et al., 2011; Rabbani et al., 2013; Baqeri et al., 2019; Dixit & Tiwari, 2020). Rabbani et al. (2013), Litvinchev et al. (2011), Dixit and Tiwari (2020) and Baqeri et al. (2019) all propose frameworks that include a multi-objective assessment when searching for the optimal portfolio composition. The process of selecting the optimal R&D projects for the portfolio can follow several different methods (Henriksen & Traynor, 1999). These selection methods can be based on mathematical programming like linear and nonlinear programming (LP and NLP) and integer programming (IP) (Henriksen & Traynor, 1999). Additionally, economic models involving the analysis of return on investment (ROI), internal return rate (IRR) and net present value (NPV) are well-established methods (Henriksen & Traynor, 1999). Decision analysis methods like the analytical hierarchy process (AHP) are also recognized methods for R&D project selection (Henriksen & Traynor, 1999). Rabbani et al. (2013) emphasize the consideration of various project parameters such as risk, expected project execution time, monetary benefits, and costs. The proposed model for project selection by Rabbani et al. (2013) is based on a multi-objective optimization program. The optimization program seeks to maximize the project portfolio value in the shape of the monetary value obtained by computing the projects' expected benefits minus the total project costs. While the program maximizes the project portfolio value it concurrently aims to minimize the risk associated with the portfolio. Baqeri et al. (2019) present a mathematical model that, like the model of Rabbani et al. (2013), searches for the optimal portfolio value, which is defined as the maximum expected project return. Unlike the model proposed by Rabbani et al. (2013), the program contains three objective functions. The two other objectives are the minimum risk and the maximum quality associated with the project portfolio composition.

Assessing the total risk associated with an R&D project portfolio requires the risk to be the sum of all the risks of the individual projects (Dixit & Tiwari, 2020). Thibadeau (2007) introduces AHP as a method for ranking project risks. She proposes that AHP is appropriate for handling intangible criteria in relation to project risks (Thibadeau, 2007). Managing the project risks demands a quantification of the uncertainties related to the project execution, and a pairwise comparison matrix is ideal for that purpose (Thibadeau, 2007: Dixit & Tiwari, 2020). As stated by Saaty (2004), the use of AHP is primarily built on the theory of evaluating scores based on individuals' comparison judgements. When evaluating a judgement according to the AHP method, the judgement is accomplished by evaluating a pair of elements with a consideration of the properties that the elements have in common (Saaty, 2004). Applying the AHP assists with decomposing the matter and, likewise, the difficulty and complexity of the evaluation of the judgement (Saaty, 2004; Bruno, Esposito, Genovese & Passaro, 2012). When evaluating the risks associated with the execution of a project, the scores are obtained based on the judgements of several stakeholders. It is essential to include multiple perceptions of the matter to decrease the possibility of a biased evaluation (Bruno et al., 2012).

Wang and Hwang (2007) contend that applying the NPV model for evaluating the expected value of the projects also includes an assessment of the risk. This is so since the NPV model underestimates the future value of the individual R&D project (Wang & Hwang, 2007).

Dixit and Tiwari (2020) propose an optimization model based on multiple objectives by combining the NPV model for evaluating the portfolio value and AHP for evaluating the portfolio risks. Applying the NPV model is done, as in the model proposed by Wang and Hwang (2007), by evaluating the sum of the NPVs of all the selected projects. Dixit and Tiwari (2020) divide the overall risk into different risk segments consisting of technical risk, schedule risk, economic risk, organizational risk, and risk associated with statutory clearance. By utilizing AHP to evaluate the risk segments for each project candidate, the overall risk objective is computed as the sum of the risk scores of the projects selected to form part of the portfolio (Dixit & Tiwari, 2020).

3. Methodological Considerations and Case Setting

This research was conducted as a case study (Yin, 2013) in the case company's R&D division using, primarily, quantitative data. However qualitative inputs for the case study originated from the company's management. Thereby also establishing elements of mixed method (Doyle, Brady & Byrne, 2009). The researchers intentionally selected a case company that had no knowledge of PPM. The case company carries out daily 'project selection/portfolio management' based on 'best practice' and know-how. Furthermore, since the company does not perform integrated PPM, its willingness, prioritization, and motivation to take part in this research is significant.

The case company's R&D division is spread across the world, and the department that participated in this research was located in northern Europe. Below is background information about the case company and about the interviews conducted for this research.

The case company participates as a sub-supplier in the rapidly expanding renewable energy market. With approximately 25 employees devoted to R&D and an annual revenue of approximately 500 million euros, the company is working hard to accomplish its objectives. However, the case company has a pool of future projects for business that is investigated within the R&D division.

The researchers interviewed six stakeholders (senior managers, project managers, and process owners) on multiple occasions. Furthermore, a workshop was held to enhance the researchers' understanding of procedures and job roles, and broaden their expertise within the R&D department.

The company's dedication to innovation and teamwork is often demonstrated by their aggressive pursuit of new initiatives and their interaction with important stakeholders. They are well-positioned to contribute to the continued development of the renewable energy sector because of their knowledge within their business segment.

The case study focuses on the PPM for innovation in the company by selecting the right pool of projects for the future portfolio. The case study itself was done together with the team management in the R&D division to create a new organizational design to test the PPM selection process for future projects. The AS-IS picture for the case company, its handling of ongoing projects, and its selection of information-sharing practices and procedures, is based on the decisions of the head of the R&D division. Arguably, the case study would be an intrinsic study because the interest is in a particular situation in the company (Lazar, Feng & Hochheiser, 2017). Therefore, it was important for the researchers to go beyond this situation by developing a broader understanding, performing what Lazar et al. (2017) define as an instrumental case study by asking questions in the hope of generating insights that go beyond the case at hand. The innovation portfolio is a part of a strategic initiative where 15-25 % of innovation spending is spent on radical innovation. Currently the team management for the case company has defined which of the projects in the pipeline should be marked as radical development projects. Radical could be defined as far-reaching and novel, e.g., instead of tightening a bolt with a torque wrench, the bolt is – in a radical context – tightened with an electric torque wrench measuring mechanical characteristics of the bolt, logging this, and sending the data to a central store for quality validation.

4. Empirical Study

4.1. Data Collection

The situation-specific information and context for this paper is the technology and innovation division in the case company, and the behaviour adaptation has a qualitative empirical link to the context in which this research question lies (Martinsuo, 2013).

The strategic alignment of the project portfolio for the case company is considered merely for the company, as if there is only one strategy within the projects and portfolio that should be aligned. Therefore, this paper does not account for multiple strategies in relation to the project selection and success criteria, nor for the interplay and relationships between different divisions inside the case company when pursuing strategic alignment.

The data were collected through semi-structured and unstructured interviews with stakeholders in the case company identified by the team management. This was done to ensure that key stakeholders involved in project management and/or involved in relation to innovation activities had the chance to share their first-hand knowledge. The key informant in the R&D division was the head of the division, who was in charge of all innovation activities. The head of R&D provided detailed quantitative and qualitative data that created the basis of this research. Six people were interviewed to create the foundation of the case study of the company and to create a comprehensive picture, with the researchers building on the qualitative layer by quantitative research to triangulate the data.

The interview template for the semi-structured interviews outlined sections of importance to the team management involved in current innovation projects. The interviewees' backgrounds, and their role and responsibilities in how the current project management process is organized, had some uncertainties because there were no connections or interfaces between the projects. This was identified through the linkages between the sum of the ongoing projects and their connection to the divisional strategy.

The overall topic originating from the project managers was their low level of capability and responsibility; they had a low impact or influence on the financial results and alignment of the divisional strategy. The interviews were summarized with the purpose of creating a qualitative foundation of information on the company's situation. Additionally, the head of the R&D division provided key insights, with confidential quantitative data, particularly to give an understanding of the business areas, contexts, and methods of project management, such as roles, responsibilities and project selection.

4.2. Data Analysis

4.2.1. Conceptual Framework

The merged framework for the selection of a project portfolio in detail and the relationships between the elements are shown in Figure 2. The new framework is not presented as an analytical method, but to outline the different stages that exist in the process, from ideation and business proposals (Archer & Ghasemzadeh, 1999) to business success, and the relationships between them (Meskendahl, 2010).

It is important to highlight that these elements are not described in this paper, because this paper explores the relationship, in project portfolio selection, between how to select a project correctly and how to select a project correctly in relation to the corporate strategy. This is done by implementing the concept.

The contribution of each element within Figure 2 is in the context of solving the MOOP.

However, each element will be explained in the context of the relationship to understand how these factors are related and how they influence each other.

Strategic orientation refers to the overall direction and focus of a company's business strategy.

This includes factors such as benefit realization, strategic plan, budget allocation, and risk-taking posture. These are the drivers for the case company's decision-making in the R&D division.

The relationship between strategic orientation and project portfolio structuring is that strategic orientation serves as the foundation for project portfolio structuring (Meskendahl, 2010; Analia-Sánchez et al., 2014).

The business objectives are interconnected and the structure of the project portfolio is aligned with the business strategy (Meskendahl, 2010). However, the strategic orientation also relates to the MOOP, because if the foundation for the project portfolio structure changes, this has to be included in how the MOOP is developed because it affects the constraints, and the disruptive rankings of projects.

The construction of the project portfolio focuses on the importance of evaluating and predicting both individual R&D projects and the R&D project portfolio. The developed model is presented as a method that can be used to aggregate the values and risks of individual R&D projects into an overall assessment of the portfolio. This highlights the importance of considering both the individual projects and the portfolio in the selection process.

Finally, business success refers to the achievement of alignment with the business objectives by managing an R&D project portfolio, the maximization of financial value, alignment with the firm's strategy, and the balancing of resource allocation (Meskendahl, 2010). These goals are presented as interrelated and mutually reinforcing, with each contributing to the overall success of the PPM process (Meskendahl, 2010).

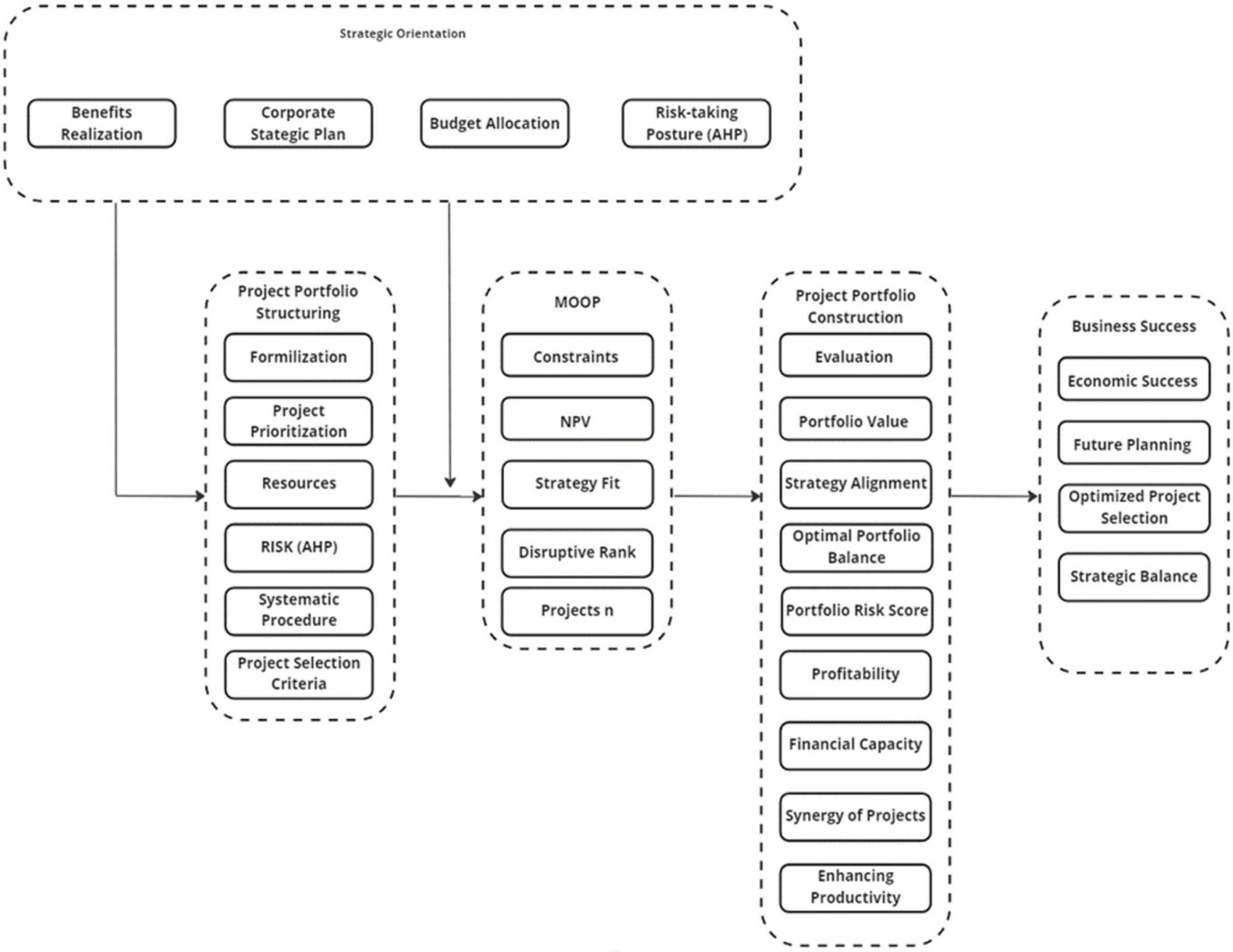

Figure 2. New conceptual framework

4.2.2. Optimal Selection of Grouped Projects and Model Development

The literature contains several mathematical models that all suit the purpose of supporting the decision-making process related to selecting the optimal projects to fit in the portfolio.

This section describes the model that is proposed as a decision-making method for the case company. The model is designed to maximize the general portfolio value and minimize the risks of the projects selected.

4.2.3. Model Description

The types of risk considered in the model are based on the focal points obtained from the semi-structured interviews with the R&D managers and cover scheduling, economic and ability-related risks. Scheduling risk primarily concerns the risk of project delay. Economic risk is primarily the risk of exceeding the budgeted financial resources. The risk associated with abilities is predominantly the risk of exceeding the skill level of the in-house personnel. The risk scores are obtained by applying the AHP method, following the approach explained by Podvezko (2009). Initially, the three types of risk are evaluated with respect to each other through the AHP method. The assessment of the compared importance of the risks is conducted by the management group and leads to a quantified risk weight of each risk type. Since each project is unique in terms of project objective and complexity, the risk of all the projects is evaluated as the next step. Each of the three risk types is evaluated for each project on a scale from 1 to 9, with 1 being equal to zero probability and 9 defined as most certain (Dixit & Tiwari, 2020).

The general portfolio value is the sum of the NPV of all the selected projects. The NPV approach is selected as the value indicator in the model, as it is probably the most popular economic valuation technique for innovation projects (Žižlavský, 2014; Chiesa & Frattini, 2009). The original principles of the NPV method are given by Equation 1 (Žižlavský, 2014).

$$NPV = \sum_{t=0}^{n} \frac{Nc_t}{(1+r)^t} \tag{1}$$

The NPV equation contains the net cashflow Nc_t generated by the R&D project in period t, with n being the total number of time periods, and the discount rate being expressed by r. The fundamental NPV method is considered appropriate for assessing the value of individual projects, since the model includes the economic risk scores.

4.2.4. Proposed Model

The model is designed to select the optimal composition of the available candidate projects. The model recognizes that each individual project has a specific planned time horizon, and a required number of resources. The model also recognizes that a certain investment strategy must be satisfied in terms of investments in different innovations. A balanced and sensible R&D portfolio is, according to the case company, one that includes radical innovation, new product introduction and existing product assistance. Because R&D project portfolio decisions are made on the basis of many considerations, a model based on multi-objective integer programming is proposed.

4.2.5. Mathematical Model

Notation:

N: total number of candidate projects,

T: total number of time periods

K: total number of risk types

L: total number of skill types

K: risk type

t: time period

l: skill type

I: index for projects

r: discount rate

Wr_k Wr_k: risk weight of risk type k

Sr_{ik}: risk score of project i for risk type k

NPV_i: net present value of project i

Rc_i: risk coefficient for project i, computed as the relative NPV of project i divided by the highest single NPV for all the candidate projects

ic_{it}: cash inflow for project i in time period t

B_t: R&D budget for time period t

f_{it} f_{it}: cost required to finance development of project i in time period t

e_{ilt} e_{ilt}: necessary number of employees with skill l to develop project i in time period t

Rw_{lt} Rw_{lt}: number of available employees with skill l to be utilized in time period t

BS_j^U BS_j^U: upper limit for budget allocated to radical innovation according to strategy *j*

BS_j^L: lower limit for budget allocated to radical innovation according to strategy *j*

$x_i = \begin{cases} 1 & \text{if project } i \text{ is selected for the portfolio} \\ & 0 \text{ otherwise} \end{cases}$

$CI_{ij} = \begin{cases} 1 & \text{if project } i \text{ is selected as a part of the portfolio composition with strategy } j \\ & 0 \text{ otherwise} \end{cases}$

$DP_{p,q} = \begin{cases} 1 & \text{if project } p \text{ is required to be selected for running project } q \\ & 0 \text{ otherwise} \end{cases}$

$CON_{s,h} = \begin{cases} 1 & \text{if projects } s \text{ and } h \text{ are in conflict} \\ & 0 \text{ otherwise} \end{cases}$

$MP_i = \begin{cases} 1 & \text{if project } i \text{ must be selected for the portfolio} \\ & 0 \text{ otherwise} \end{cases}$

$$\text{Max} \sum_{i=1}^{n} NPV_i \tag{2}$$

The first objective (2) of the model is to maximize the portfolio value. This is done by maximizing the sum of the NPVs for the selected projects. NPV_i, which is the net present value for project *i*, is calculated in the model as in Equation (3).

$$NPV_i = \sum_{t=1}^{T} \left(\frac{-f_{it}}{(1+r)^t}\right) + \left(\frac{ic_{it}}{(1+r)^t}\right) \cdot x_i \tag{3}$$

The NPV formula shown in Equation (3) demonstrates that the project cost f_{it} and the cash inflow ic_{it} are calculated for the total number of time periods *T* for which the project is planned to run.

$$\text{Min} \sum_{i=1}^{n} \sum_{k=1}^{K} ((Sr_{ik} \cdot Wr_k) \cdot x_i) \cdot Rc_i \tag{4}$$

The second objective function (4) seeks to minimize the sum of all the risk scores. This is achieved by minimizing the sum of all the project risk scores Sr_{ik} multiplied by their individual weights Wr_k subject to:

$$\sum_{i=1}^{n} (f_{it} \cdot x_i) \leq B_t \qquad \forall t, \tag{5}$$

$$\textstyle\sum_{i=1}^{n} (e_{ilt} \cdot x_i) \leq Rw_{lt} \qquad \forall t, l, \tag{6}$$

Constraint (5) essentially ensures that the sum of the costs in time period *t* required for financing the development of the selected projects is less than the allowed budget in that time period, B_t. Constraint (6) is formulated so that the sum of the number of employees with skill l required to develop the selected projects within time period t does not exceed the available number of employees with skill *l* within the same time period, which is Rw_{lt}.

$$\sum_{i=1}^{n} \sum_{t=1}^{T} (CI_{ij} \cdot f_{it} \cdot x_i) \leq BS_j^U \qquad \forall j, \tag{7}$$

$$\sum_{i=1}^{n}\sum_{t=1}^{T}(CI_{ij}\cdot f_{it}\cdot x_i) \geq BS_j^L \qquad \forall j, \tag{8}$$

Constraints (7) and (8) are designed to ensure that the project portfolio includes enough radical innovation. This is done by defining that the sum of radical innovation project costs selected for the portfolio must be within a certain range, higher than Bs_j^L and lower than Bs_j^U. The upper and lower limits of the budget allocated to radical innovation are defined by strategy *j*.

$$\sum_{i=1}^{n}(MP_i\cdot x_i) = \sum_{i=1}^{n} MP_i \qquad \forall i, \tag{9}$$

$$\sum_{i=1}^{n}(DP_{p,q})\cdot x_{qi} - x_{pi} \leq 0 \qquad \forall q,p, \tag{10}$$

$$\sum_{i=1}^{n}(CON_{s,h})\cdot x_{si} + x_{hi} \leq 1 \qquad \forall s,h, \tag{11}$$

$$x_i \in \{0,1\} \qquad i \in \{1,2,\dots,n\} \qquad t \in \{1,2,\dots,T\} \qquad k \in \{1,2,\dots,K\} \qquad l \in \{1,2,\dots,L\}$$

Constraint (9) ensures that projects that are for some reason required to be selected are indeed selected. Both constraint (10) and constraint (11) consider the relationships between projects. Constraint (10) ensures that if the selection of project *q* depends on the selection of project *p*, project *q* can only be selected if project *p* also is selected. If there is a contradictory relationship between project *s* and project *h*, constraint (11) ensures that both cannot be selected.

5. Analysis and Results

5.1. NSGA-II

To solve the MOOP, the framework applies NSGA-II (Verma et al., 2021). NSGA-II is an effective algorithm for solving MOOPs and is one of the most popular search algorithms for doing this. The algorithm provides a diverse set of optimal solutions within the Pareto front (Verma et al., 2021; Awad, Abouhawwash & Agiza, 2022). In relation to portfolio problems, NSGA-II is commonly used for maximizing benefits and minimizing associated risks (Awad et al., 2022). When searching for the set of optimal solutions, the algorithm applies the concept of Pareto dominance for sorting population members (Verma et al., 2021). For the two objective functions described above, dominated solutions can be defined for a set of solutions $S = \{s_1, s_2, \dots, s_n\}$ $S = \{s_1, s_2, \dots, s_n\}$. When denoting a specific solution, if s_1 is not ranked lower than s_2 in regard to both of the two objectives and simultaneously outperforms s_2 in one of the objectives, s_1 can be described as the dominant solution (Kochovski, Paščinski, Stankovski & Ciglarič, 2022). The Pareto front gives the set of non-dominated solutions (Kochovski et al., 2022). The case results are presented through a Pareto front.

5.2. Case Results

This section highlights the results of the MOOP based on data obtained from the team management in the case company.

Risk-types	Schedule	Economic	Ability	Wr_k
Schedule	1,000	3,000	7,000	0,677
Economic	0,333	1,000	2,333	0,226
Ability	0,143	0,429	1,000	0,097

Table 1. AHP based risk-type weightings

#	1 if disruptive	Project description	Sr_{ik}			$\sum_{t=1}^{T} ic_{it}$	f_{it}			
			schedule	economical	ability	(milion EUR)	1	2	3	4
1	1	Software design	7	5	4	2,4	0,2	0,25	0,15	0,3
2	1	Product design	5	4	4	1,4	0,12	0,1	0,09	0,2
3	1	Machine learning	1	1	2	0,65	0,1	0,03	0,05	0
4		Inspection controller	2	3	1	0,93	0,09	0,06	0,06	0,03
5	1	Supplychain algorithm	3	2	2	0,81	0,075	0,075	0,06	0,15
6		ERP setup	1	2	1	0,87	0,06	0,045	0,06	0,24
7		Product data design	4	4	2	1	0,1	0,2	0,2	0,1
8		CAD-CAM automization	5	4	3	1,2	0,15	0,12	0,1	0,14
9	1	Modularization	6	5	3	3,1	0,5	0,2	0,2	0,2
10		RPA project	2	2	2	0,95	0,2	0,05	0,05	0,1
11		SCADA-system	5	4	2	2	0,4	0,15	0,15	0,1
12	1	PCS platform	6	3	3	1,5	0,2	0,2	0,2	0,2
13		3D scan	2	1	1	0,5	0,12	0,12	0,05	0
14	1	Simulation platform	2	2	6	0,85	0,15	0,15	0,15	0,1
15		Sensor application	3	7	3	0,8	0,12	0,12	0,12	0,12
16	1	Production Hardware	4	8	2	2,1	0,5	0,32	0,3	0,2
17		Mobile CNC	1	4	2	0,9	0,15	0,06	0,06	0,03
18		IoT connectivity	5	4	4	1,65	0,32	0,3	0,1	0,1
19		Sales quotation	2	2	2	1,5	0,28	0,16	0,16	0,25
20	1	NPD	8	6	3	2,5	0,45	0,2	0,35	0,2

Table 2. project candidates and their individual data

Table 1 displays the AHP-based risk type weightings, and Table 2 presents the candidate projects and their individual data, together with data such as the human capacity needed and a classification of project interdependencies. To achieve the case solution, the MOOP was programmed in Python (van Rossum, 1995) within the MOOP library named Pymoo (Blank & Deb, 2020).

The planning period is set at four years, with an innovation strategy of a minimum of 15% and a maximum of 25% of the total four-year budget to be spend on disruptive innovation.

The project interdependencies are defined as project 1 being dependent on project 7, project 2 being dependent on project 7 and project 11 being dependent on project 15. The yearly budget constraints are determined to be 1.92, 1.31, 1.19 and 1.24 million euros, respectively, for years one to four. The internal discount rate is set at 4%. Finally, there is an availability of seven software engineers, six mechanical engineers and five industrial engineers each year.

The Pareto solutions obtained are displayed as a Pareto front in Figure 3 with the solution-set being described in Table 3. The Pareto solution shows the direct impact of the conceptual factors on the project portfolio structuring. Furthermore, it shows the moderation of the relationship between the portfolio value and the portfolio risk scores, which showcases the analytic posture of the portfolio and the interplay between the portfolio structuring and the project portfolio construction with a MOOP perspective. The MOOP proposition is illustrated within the Pareto solutions, which are merged into a managerial decision-making mechanism.

The Pareto front shows the optimal solution set, with the individual solutions representing varying trade-offs in relation to the objective functions. It is clear from the results that the trade-offs of the two best solutions in terms of portfolio value do not align with the trend. This indicates that targeting one of the solutions within the range of highest portfolio values significantly compromises the risk score. By further analysing the solution set, clear trade-off patterns arise from specific candidate projects. Table 3 shows that multiple solutions are within a close objective range, which allows a certain selection freedom.

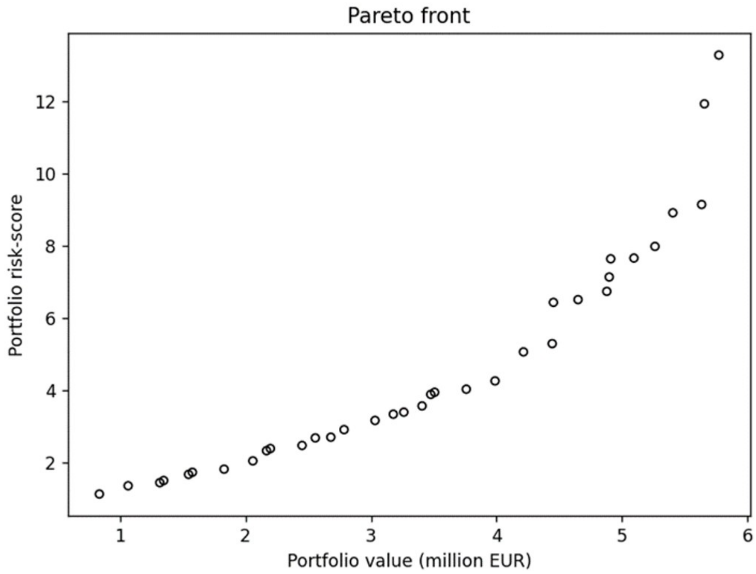

Figure 3. Pareto solutions obtained

6. Discussion

This paper presents a conceptual framework for PPM as a method for R&D project portfolio selection using a multi-objective optimization program. The framework was created by merging the framework of Meskendahl (2010) with quantitative framework elements2. This is to create a multi-objective optimization program construct. This was developed to address a need for a shared understanding of a project portfolio selection method for management professionals and research communities, and an accurate method for analysing R&D projects in a systematic manner to optimize corporate objectives.

6.1. Framework Development

This paper has certain implications for PPM, as the conceptual framework developed expands existing theories. Originally, the core approach of the framework suggested by Meskendahl (2010) had theoretical factors for structuring the project portfolio, whereas this paper extends these findings by exploring relevant quantitative insights from adjacent disciplines. By incorporating and exploring quantitative methodology, this paper aims to provide a more rigorous and holistic approach to PPM, allowing the values and risks of proposed projects to be considered to balance business and performance outcome.

The theoretical components developed and recommended in this paper can be used for further research in the field and built upon to improve PPM theory. Certain inferences can still be made that may have an influence on practice, although the management implications of the conceptual model are restricted until empirical validation.

The comprehensiveness of the conceptual framework developed, which spans the full project cycle from strategic planning through PPM and the quantification of business performance, is one of its key strengths. Instead of concentrating just on the results of individual projects, this selection method offers a balanced comprehensive evaluation of the corporate profit and strategic alignment of the R&D portfolio for the risk-averse decision maker in an uncertain environment.

Pareto solutions	Portfolio value (million EUR)	Portfolio risk-score	Projects, x_i is 1 if selected																			
			x01	x02	x03	x04	x05	x06	x07	x08	x09	x10	x11	x12	x13	x14	x15	x16	x17	x18	x19	x20
1	0,84	1,12			1		1								1	1			1			
2	1,55	1,66					1									1						
3	5,09	7,65			1		1								1	1						
4	1,06	1,35		1	1	1						1			1	1					1	
5	5,77	13,27					1								1	1						
6	2,06	2,04			1				1	1		1	1	1	1		1			1		
7	2,68	2,70			1		1	1							1	1						
8	3,51	3,94			1		1	1							1	1			1			
9	3,18	3,33					1	1				1			1	1			1		1	
10	1,32	1,43			1		1	1								1			1		1	
11	1,58	1,73			1		1									1						
12	1,35	1,50					1	1							1	1						
13	2,20	2,38					1	1								1						
14	3,41	3,56					1	1							1	1			1			
15	3,26	3,39			1		1	1							1	1			1		1	
16	1,83	1,81			1		1	1				1			1	1			1			
17	2,79	2,90			1		1	1								1						
18	2,45	2,47			1		1	1							1	1					1	
19	4,45	6,43			1		1	1								1			1			
20	3,99	4,25			1		1	1	1	1		1			1	1			1			
21	3,48	3,87			1		1	1				1			1	1			1		1	
22	3,03	3,16			1		1					1			1	1			1		1	
23	2,56	2,68			1		1	1				1				1			1			
24	4,44	5,28			1		1	1								1					1	
25	3,76	4,02			1		1	1	1			1			1	1			1		1	
26	4,88	6,73			1		1	1				1				1			1		1	
27	4,21	5,06			1		1	1				1			1	1			1	1	1	
28	4,90	7,13			1		1	1	1			1				1			1		1	
29	5,63	9,13		1	1			1	1			1			1	1			1		1	
30	4,91	7,63		1	1			1	1	1		1			1	1			1		1	
31	4,65	6,50			1	1	1		1			1			1	1				1	1	
32	5,26	7,93			1		1	1				1				1			1	1	1	
33	5,40	8,90		1	1			1	1			1			1	1	1		1		1	
34	5,66	11,92		1	1			1	1	1		1				1			1		1	

Table 3. multiple solutions are within a close objective range

However, the framework and the MOOP model are not limited to a particular industry or project type, which makes them broadly applicable to PPM research in various industries. This flexibility allows companies to adopt the framework to leverage and optimize their PPM practices.

The paper's notable limitation is that the conceptual framework needs to be empirically validated to confirm its validity and reliability. In addition, this paper is based on a case study with a focus on a specific need for internal projects, which may limit how it can be expanded and explored for other stakeholder groups.

The proposed framework creates considerable advantages for PPM, while also presenting new challenges. The integration of the MOOP enables the reliability and accountability of real-time validation of R&D project portfolio selection and construction data, resulting in a greater quantity of reliable data that can be used in the decision-making mechanism for project selection and prioritization in future portfolio construction decisions. The integration of this framework ensures a timely termination by reducing and maximizing the innovation pipeline of good and bad projects to accurately reflect the strategic alignment within a given company.

However, challenges may occur from conflicts with the existing portfolio, as this framework creates predictability by being implemented as a managerial decision-making mechanism. This approach may conflict in a dynamic scenario in which the budgeting approach relies on traditional metrics. Therefore, the framework does not account for project progression and economical reliability, or other linear application methods, as the MOOP does not monitor project progression and does not actively reveal when the portfolio is in a high-risk situation. However, a multi-simulation of the current health of the portfolio provides a good sense of how close projects are to their targets and business success. This can be done at any stage within the portfolio to help measure the value of the current project portfolio construction. Finally, the framework ensures that management can allocate resources to operationalize the portfolio value and the portfolio risk scores from a decision-making perspective that is aligned to the business strategy, as projects enter the portfolio. This approach challenges the traditional approach of annually budgeting innovation projects against specific projects.

6.2. Limitations

The suggested framework is relying on useful and relatively well-established data-sources. Clearly, the PPM activity is tasked with quite some activity in budgeting, cost estimation, resource need, staff allocation, etc. However, in many industries this is anyhow expected regardless of PPM methodology. Also in financially challenged organizations, external financial parties might clearly expect resources to be spend economically and carefully. Anyhow, this study has limitations regarding depth and magnitude of projects. The framework do definitely not cover "mega-projects", also "task-sized" projects are better managed in different ways. So, the scoping is aimed at mid-sized projects in the e.g. 0,2-5 million EUR range. The framework is furthermore not taking bias and misrepresentation into account even if this is frequent factors in PPM.

6.3. Implications

Implications. The findings could suggest attractive implications for management as light is shed on the objective dimension of PPM. Obviously, management has any right to exercise a subjective decision-making from any reason, but the frameworks support to transparency and optimized PPM can be attractive in many corporate contexts. As an implication for research, the suggested approach adds to the PPM literature with an approach rooted in the mechanical industry. The findings propose an open-minded and documented pathway of data collection of constraints hopefully inspiring further interest in both a priori and post-project performance analytics. For both management and research, the approach can positively contribute to understanding decision-making, project governance, and help understanding of "innovation pipelines" in "traditional" industries. As the case company is active in renewable energy technologies, resource spending and PPM must also be seen as critical to the spending of necessary but scarce resources in the field. Not the least considering the high level of uncertainty characterizing "green" industries in terms of global competition, upward cost drivers and downward revenue drivers.

6.4. Future Research

Industries, and especially industries in areas critical to societal change, need to apply methodologies minimizing risk and optimizing value. A number of strands for future research is expected. Firstly, organizations using the suggested framework (or similar) must have lessons learned processes in place in order to document good PPM governance. Continuous validation and adaptation of the framework is interesting. Secondly, as many organizations are implementing various hybrid project management approaches, the impact of this could benefit the model. Especially, and in this field, organizations might combine stage-gate / linear approaches with agile approaches and DevOps philosophy. This implies that the project organizations have cost and risk exposures in various configurations: Long term risk of linear (large) timelines, short term agile timelines, and DevOps bridging development and operations. Such R&D models are highly interesting in the future research. Thirdly, the suggested mathematical approach can benefit from artificial intelligence (AI) especially generative AI and machine learning. Future research will include these technologies to optimize the model framework.

7. Conclusion

The selection of projects for the R&D portfolio is done to ensure one common project portfolio decision process and initiate and sustain necessary, sufficient, and suitable projects to meet the constraints and the strategic objectives. As a result of the successful framework for the selection of a project portfolio, the ideation and business proposals are captured into the context of PPM. The quality of the portfolio and business proposals are not specifically assured in today's business in the case company. Therefore, the data and factors on which the management make their decisions to create the selection are relatively fuzzy. However, the indicators and prioritization for selecting and rejecting projects are achieved for a defined scenario creation originating from the team management, which is then evaluated as business success.

The optimal selection of the grouped projects will prioritize and improve the portfolio of business opportunities in the R&D division to maximize business impact via the investment of adequate funding and resources, balanced by the team management with the horizontal perspective of the short- or long-term capabilities needed to successfully execute the chosen projects. The project mandates needed to establish the selection of projects are set solely done by a review session with the team management in the case company.

The selection of the portfolio projects is performed using a transparent and selective method that selects projects based on maximizing the NPV and minimizing the risk, within defined constraints. The method created in this research builds on the principles of quantifying the maximum value and minimizing the risk according to the R&D constraints and strategy. Therefore, it will be possible for the case company to increase the value of the portfolio of initiated projects with transparency and no hidden activities that may appear during the development phase as was the case with the former 'best practice'. This method lets the case company decide how to spend its time and money on where it adds most business and portfolio value, by simplifying and making it easier to select projects for the portfolio through a clear and specific structure, which only focuses on what the case company must do.

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